DUAL MODE (MWIR AND LADAR) SEEKER FOR MISSILE DEFENSE

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Abstract

This paper identifies the key weapon system requirements of a dual mode seeker solution that performs mission critical target discrimination, tracking and aimpoint selection during stressing conditions. System level trades made to integrate ladar into a current generation MD seeker are summarized. Proof of concept hardware was developed to both demonstrate feasibility and collect field data on simulated threats and decoys. The packaging, thermal and boresight of separate focal planes are addressed. Operationally the seeker is cued by ground based radar to the location and direction of the threat cloud (threats and non-threats). The IR seeker tracks these objects (when separated) and provides a prioritized location map for the ladar. The ladar is used to sequentially and periodically interrogate these objects to separated CSO's and extract micro-dynamic information used for discrimination. The paper details why a Geiger mode flash ladar was selected for this application and how its output is used in discrimination. Dual mode images of threat and decoy objects are presented at various signal levels and resolutions to simulate a typical engagement timeline. This dual mode seeker will be used to gather captive carry signature data on near future MD tests.

Introduction

Nations of concern will evolve robust countermeasures and tactics in an effort to defeat Missile Defense (MD) systems. This, coupled with a cluttered battle space (booster debris, previous intercepts and raid attack), results in a situation in which there are numerous closely spaced objects (CSO's). Incorrect target discrimination, during these stressing conditions, by current generation single color IR seekers will substantially reduce the effectiveness of hit-to-kill defensive weapon systems. This paper identifies the key weapon system requirements of a dual mode seeker solution that performs mission critical target discrimination, tracking and aimpoint selection during stressing conditions. The deployment of a synergistic seeker with passive IR and ladar discrimination, coupled with ground based radar, greatly reduces the effectiveness of foreseeable countermeasures.

BAE System has developed and evolved concepts for dual mode seekers (active and passive) for MD applications. While the intercept domains of theater/terminal, midcourse and boost phase will use and benefit from ladar in varied ways, the common conclusion is that ladar provides significant performance improvement over the full engagement during stressing conditions. For long range detection with reasonable laser power, the ladar must have a small beam width. Since radar and satellite target handoff baskets are large in angle space an IR sensor is needed to locate the objects of interest before the ladar can be positioned on the object. The IR sensor also performs bulk filtering to reduce the number of objects that the ladar must interrogate. These active concepts include both direct detect (Angle, Angle, Range) ladar and coherent detection (Angle, Angle, Range, Doppler).

Dual Mode Seeker Requirements

In order to determine dual mode seeker requirements, a list of potential functions and benefits of ladar was developed as show in Table 1.

Ladar Role	Requirement Impact
CSO Discrimination	Resolution
3D to 3D TOM	3D Track Accuracy
Intense Source Rejection	Spatial, Spectral and Temporal Bandwidths
Aimpoint Determination	Transmitter Beam Width Control
Support Multi-color	Not a Driver
Support Threat ID	Transmitter Beam Width Control
Predictive Intercept	3D Track Accuracy

Table 1 Ladar Role and Requirement Drivers

The CSO problem requires a high resolution ladar receiver, for example as shown in Figure 1. Here a ladar with 30 μrad detector angular subtense (DAS) is viewing objects that are 2.5, 5 and 10 meters apart. Signal processing techniques can be used to improve

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the object tracking to less than one ladar pixel. This will enable CSO track separation starting at 300 – 500 km, depending on object separation. A typical LWIR sensor with a large (20cm) aperture would have a diffraction limit (at 8 microns) of about 100μrad. For IR only the CSO's would not be separated over a significant portion of the engagement. Another important aspect of early separation of the tracks by the ladar, is the tagging of IR pixels that contain more than one object. This combined with range to the object will have a very positive effect on the performance of multi-color IR discrimination. Without this information an IR pixel with multiple objects will be seen as an average of temperature/area of the objects.

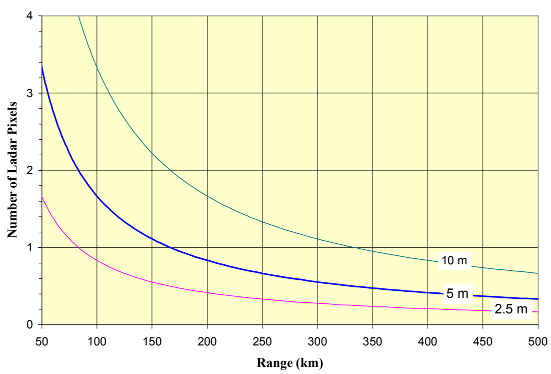

Figure 1. Number of Ladar Pixels for Three CSO Separations

Current MD seekers must correlate the 3D target object map (TOM) generated by surface based radar to the 2D scene from IR sensor. Measurement error, seeker attitude and position errors and latency all conspire to increase the risk of incorrect target handoff. The dual mode seeker is able to offset this risk by providing a 3D to 3D correlation with the TOM. This become crucial in a cluttered battle space where the IR sensor will likely see many more objects than are in the TOM.

This cluttered battle space will also produce some intense sources (previous intercepts, IR countermeasures and other energetic events) that will impair or preclude object tracking. The ladar will be actively tracking in another band that will be less influenced by these

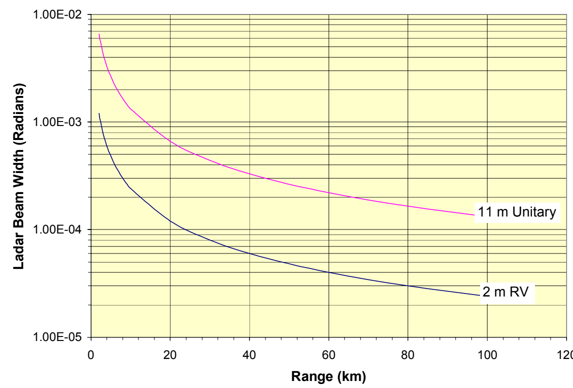

Figure 2. Beam Growth Required in Endgame.

sources and can maintain track as well as aid the IR track to coast longer using 3D information. These background conditions drive the ladar to have a narrow spectral bandpass to limit the received energy. Equally import is the ability to have a narrow range gate and perform frame to frame range processing. The small DAS, driven by other requirements also reduces the amount of unwanted signal. In short, simultaneous active and passive tracking is difficult to defeat.

The endgame places a different set of requirements on

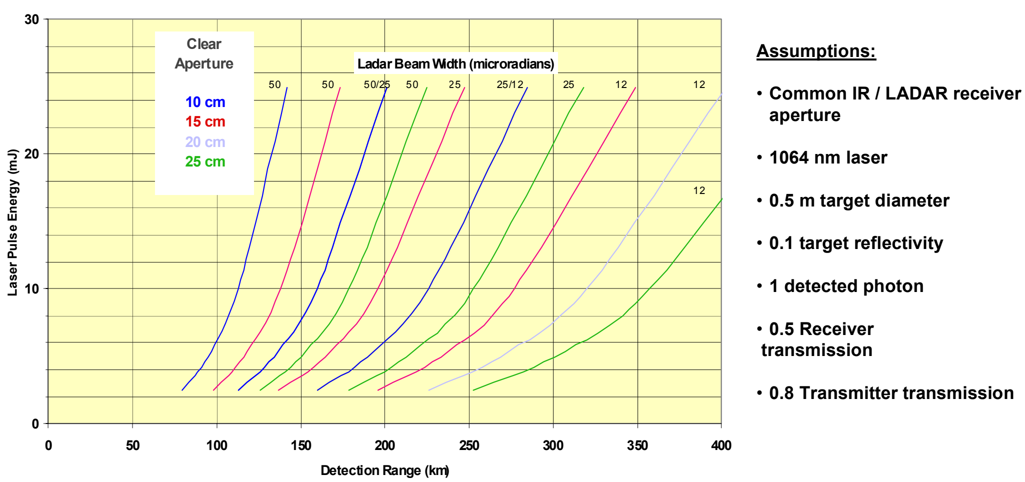

Figure 3 Ladar System Trade Space

the ladar. Here a much wider laser beam is need to keep the object fully illuminated as the range decreases. Figure 2 shows the amount of beam expansion required for a 2 m long RV and an 11 m long unitary missile viewed at 90 degree aspect (broadside). The curves assume a 20 % overfill to relax the system pointing requirements.

The ladar can aid in target identification by providing unique information throughout the engagement. These include details on size and shape/features, estimate of mass, measurement of micro-dynamics, reflectivity at the laser wavelength and IR emissivity. The mass is estimate at those altitudes where there is sufficient interaction with the atmosphere [1]. The emissivity is estimated by measurements in multiple IR bands knowing the size and range to the target. This information fused with surface based radar will yield a high probability of target ID.

The required acquisition range is a key ladar requirement since it drives the trade space of laser power, laser beam width and collecting aperture. This trade space is illustrated in Figure 3 for a direct detection ladar operating in the Geiger mode where a single returned photon is detected. Curves represent 4 aperture sizes (10 to 25 cm) and 3 beam widths (50, 15 and 12.5 µrad). These curves are useful to explore system level trades, for exact performance determination detail target signatures and engagement geometries are required.

Ladar Trades

A top level ladar trade tree is shown in Figure 3. The

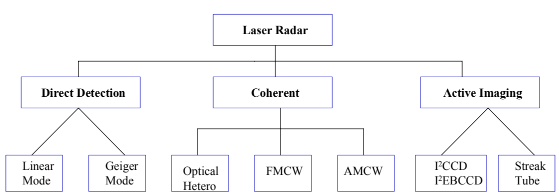

Figure 3 Top Level Ladar Trade Tree

need for long range acquisition with practical hardware implementations, drives the ladar to use the most sensitive techniques available, namely, coherent detection and Geiger mode. Under the right system conditions they both can reach the shot noise limit. The right conditions for Geiger mode are low background and manageable (via short range gate) dark current. Low background is achieved by optical filtering, range gating and engagement management (driven by the desire to have low IR backgrounds). The right conditions for coherent detection are low local oscillator noise and a stable optical system to maintain high heterodyne efficiency over the receiving array. Given that they can be made to have equivalent sensitivity, what are the trade attributes. The major trade is target information and features and at what point in the engagement are they available. During acquisition and track initiation both system provide AARI as shown in Table 2. The Geiger mode system can not measure intensity directly but can derive it by using a series of laser pulses. The coherent system can provide target dynamics with Doppler processing. This process can be enhanced by the additional of waveform modulation as is used in the Doppler radar community. The Geiger mode system in this unresolved regime can make target velocity calculations based on the range measures at high rate (typically 10's of kHz). As the target becomes resolves the Geiger mode system can measure target dynamics when sufficient pixels are available. As the engagement transition to the endgame, accurate amipoint selection and guidance, not discrimination, are the drivers. Here both systems should be equal, but it may become necessary to have a hybrid coherent system where the inner part of the receiving array performs coherent detection and the outer is linear mode direct detection. This would reduce the area where coherence must be maintained.

<table>
<tr><td>Endgame</td><td colspan="2">Track</td><td>Acquisition</td></tr>
<tr><td colspan="2">Resolved Target</td><td colspan="2">Unresolved Target</td></tr>
<tr><td colspan="4">Geiger Mode Ladar</td></tr>
<tr><td colspan="2">AARI
Target Dynamics</td><td colspan="2">AARI</td></tr>
<tr><td colspan="4">Coherent Ladar</td></tr>
<tr><td>AARI</td><td colspan="3">AARI and Doppler
Target Dynamics</td></tr>
</table>

Table 2. Ladar Information Over the Engagement Space

The laser wavelength trade considerations are; the conversion efficiency from input power to laser power, quantum efficiency of available detectors, required resolution for a given aperture size, target reflectivity and spectral and temporal separation from energetic clutter. Also for photon detection, there are more photons per unit energy as the wavelength is increased.

Objective System Design

An objective system concept was developed that addresses the key system requirements, while maintaining cognizance of kill vehicle (KV) constraints. The trade of pointing and stabilization approaches drives the system design more than any other. For passive IR three approaches are typically used, gimbaled, scan mirror or strap down. In a strap down approach either the detector array must have a large FOV or the KV is attitude controlled and maneuvered to cover the FOR.

For a dual mode seeker, where the laser must be position over the entire IR FOV, a scan mirror is the most efficient for overall packaging. For example in a gimbaled approach, the laser needs to either be on gimbal or mirrors used to transport the laser output beam to on gimbal optics.

The approach selected for the objective system is shown in Figure 4. Depicted in the figure is a small diameter off axis optical system that is used for collection of broadband IR and laser returns. A dichroic filter is used to separate the IR and laser returns and direct them to the corresponding FPA. A narrow bandpass filter (1 nm) is used to reduce the background into the ladar FPA. Stabilized mirror technology from SMDC's AIT program is used for both IR line of sight stabilization and pointing of the laser to the IR pixels of interest. A large mirror is used to positions over the large FOR and a small is used to position the laser over the IR FOV. This high performance mirror has the ability to point the laser to within 5 μr in 1 ms. Both mirrors have sufficient bandwidth to operate in typical KV environments.

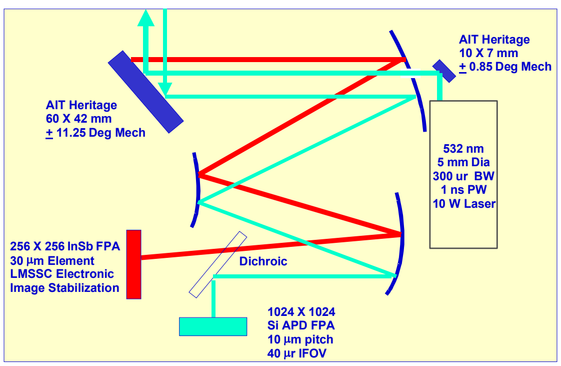

Figure 4. Objective System Concept

The objective system uses a 532 nm laser to improve resolution and a silicon APD array. Operating in the Geiger mode. Geiger mode operation is achieved by biasing the APD above its breakdown voltage, which typically provides gains of 10^6. The device is current limited so that current will stop flowing after each avalanche event. These events can be triggered by the conversion of a photon to an electron or by a thermal generated electron in the bulk silicon which is characterized by the dark current. The maximum allowable dark current increases as the range sample time (range gate) is decreased. For MD applications the initial range uncertainty is typically 10's of meters to say 100 m. This means that the APD can operate with relatively high dark count rates (up to the low kHz). If it ever becomes necessary to operate with long rage gates, then the silicon can be modestly cooled using a thermal electric cooler.

APD's are available using HgCdTe and InGaAs technologies for operation with near IR laser sources. Noise and cooling requirement trades relative to silicon as well as other wavelength trades listed earlier will determine the selection.

A large ladar FPA is envisioned that matches the IR FOV, but at higher resolution. For example if the IR array is 256 x 256 then at four times the resolution the ladar FPA would have to be 1024 x 1024. MIT/LL has been developing low bias voltage silicon APD's for operation in the Geiger mode. The details of this development are described in several publications [1-4]. The current arrays are 32 x 32 element design to operate at 532 nm. They have 11 μm diameter APD's on 100 um pixel pitch. Micro lenses are used to improve the fill factor. Lincoln Laboratory has also developed a pixel timing circuit that measure the time from the generation of the outgoing laser pulse to the first returned photon. It uses a CMOS process and has a timing resolution of 0.5ns (3-inch range resolution). There is wide interest in these arrays, which will help in the development of large format FPA's.

For Geiger mode operation a narrow laser pulse is required to provide sufficient range resolution and accuracy.

Brassboard Design

Figure 5 shows the Ladar unit. The telescope is the main body in the center. with the laser mounted on the back of the telescope to the right. The ray trace in Figure 4 indicates the laser is projected through the primary

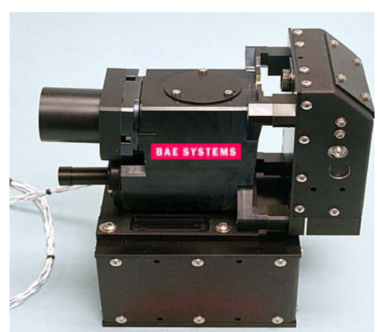

Figure 5. Breadboard Ladar Unit

mirror. The breadboard as shown has the laser mounted on the back of the telescope to the right and the laser is fired over the top of the telescope. A solar shield and a .010um bandpass filter was added to the design to facilitate daytime testing.

Test Results

Figure 6 shows the initial image taken with the bread unit shown in figure 5. Typical of 2-D data it is not clear what the actual target shape is or what the sources of the "noise" (additional data points) are.

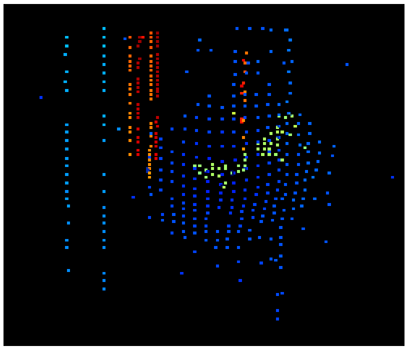

Figure 6. Initial Ladar data

The image in figure 6 is actually 3-D since each point has both angle-angle data as shown but also includes a range component. The range component allows the image to be rotated as shown in figure 7. Once rotated, it becomes clear that the target is in fact conical and the additional "noise" is part of the supporting structure.

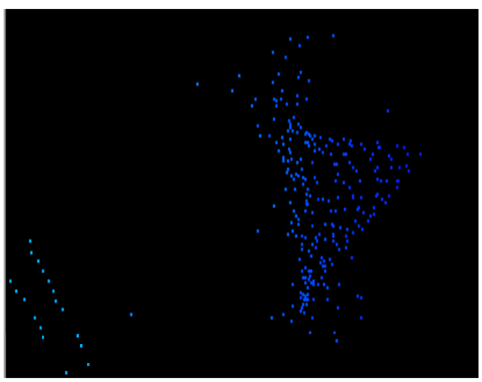

Figure 7. Ladar AAR image rotated 90 degrees showing the conical shape.

Complex micro-motion can be detected from multiple frames were taken over time.

Conclusions

The role and benefits of Ladar as an adjunct to a passive sensor in a dual mode seeker have been explored and defined. Clearly the performance benefits are well worth the added complexity of the seeker design. Further, todays technology can prove high performance Ladar capability in a relative small mass and volume penalty.

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